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ABSTRACT

High-intensity paper drying processes involve the complex phenomena of multiphase transport in porous media. The role of simultaneous gas-liquid flows in the fibrous web during high-intensity drying is of special interest. In discussing high-intensity drying, we will specifically consider impulse drying, an emerging technology in which gas-liquid flows may be especially important.

Numerical models have been developed to predict the transient heat transfer, vapor pressure development, and vapor-liquid flow in high-intensity processes. Here, we compare results from independent modeling efforts at two institutions, including a highly idealized moving boundary model for impulse drying (IPST) and an extensive generalized model for paper drying (SUNY-Syracuse) applicable to conventional and high-intensity conditions. Though neither model can fully capture the complex details of impulse drying, the results give some insight into possible heat transfer and flow mechanisms in impulse drying and related high-intensity paper drying processes. Both efforts point to the importance of vapor formation. Pressurized vapor can displace liquid water out of the web. Sheet permeability is an important factor controlling the development of internal vapor pressure. Numerical results also show that the physics of vapor formation and liquid flow are similar to that of a heat pipe. As drying progresses, the location of the heat pipe advances through the web. Continued vaporization and condensation in the web are major heat transfer mechanisms.

INTRODUCTION

In this paper, high-intensity drying refers to drying techniques in which high internal web temperatures lead to vapor pressures that exceed the ambient pressure, resulting in vapor transport primarily by bulk pressure gradients rather than by diffusion. A variety of high-intensity paper drying processes are in use or nearing commercialization. Examples include the gas-heated drum dryer (1), press drying (2), the Tem-Sec press (3), thermal-vacuum drying (4,5) and impulse drying (6-12). Here, we will focus on impulse drying, where vapor formation in the sheet may play a critical role.

Impulse drying is a novel water removal process first proposed by Wahren (6) and subsequently developed at the Institute of Paper Science and Technology (IPST) (7,8,12). At a superficial level, impulse drying can be described as a variation of wet pressing, with one roll heated to 250-400°C (see Figure 1). Much higher temperatures are used than in other existing thermally-assisted pressing processes. As a moist sheet (say, 30-50% solids) passes through such a nip, intense heat transfer occurs, with peak fluxes ranging from 1 to 10 MW/m^2, rapidly tailing off to fluxes near 0.2-1.0 MW/m^2 during the 15 to 100 ms event. The process has the potential to give higher dryness levels than wet pressing while using less energy than conventional cylinder drying.

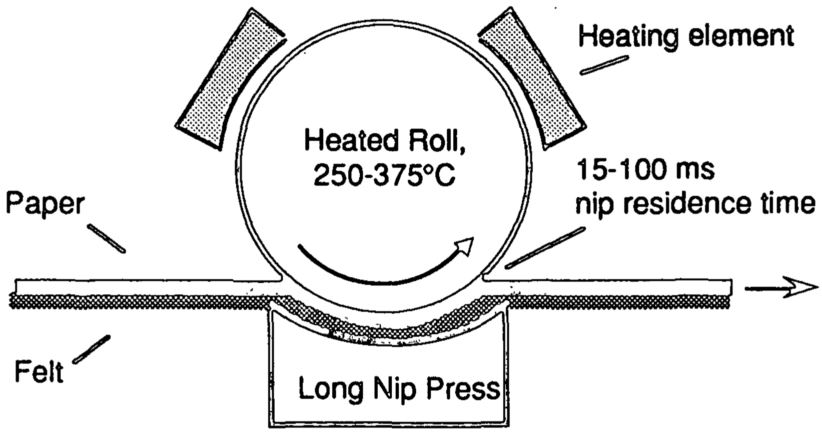

FIGURE 1. The impulse drying concept.

Impulse drying not only offers the potential for energy and capital savings over traditional dewatering and drying methods, but can give significantly improved paper properties as well (8-12). The high temperatures in impulse drying enhance surface fiber conformability and interfiber bonding, resulting in increased tensile strength and surface smoothness. Recent studies of impulse drying in newsprint (13) have confirmed IPST results (14) for other grades, showing that in addition to the potential for substantial energy savings, impulse drying gives improved smoothness and higher strength. Strength improvement has stimulated intense industrial interest in impulse drying, for it would allow a required strength to be achieved with less fiber or with alternative raw materials.

Successful impulse drying requires proper delivery of heat to the sheet. Orloff has demonstrated that properly heated ceramic-coated rolls overcome early difficulties in impulse drying and may even require less energy than standard metal rolls (15). The observed success with ceramic-coated rolls is actually greater than simple heat transfer analysis would predict. Indeed, the physics of impulse drying are not fully understood and have been the subject of some controversy recently (16,17). Recent research results toward understanding impulse drying physics and the role of vapor formation will be discussed below.

PHYSICS OF IMPULSE DRYING

Measurements of water added to the felt by impulse drying and by wet pressing showed that about 90% of the extra water removed by impulse drying in 250 g/m^2 wet sheets is in liquid form (18). This is consistent with earlier measurements made by Lavery (19). Enhanced *liquid* water removal is the key to energy savings in impulse drying.

Based on their exploratory work, Arenander and Wahren (20) proposed a vapor-liquid displacement mechanism for impulse drying based on the role of steam in the sheet. The possibility of such a mechanism in high-intensity drying has also been explored by Ahrens and Åström (21). The high temperatures at the surface of an impulse-dried sheet correspond to vapor pressures which exceed the hydraulic pressures generated in much or all of a press nip. As a result, phase-change heat transfer will occur in the nip, leading to a pressurized vapor zone that can increase the hydraulic pressure which drives liquid out of the sheet into the felt. Both Holm (22) and Ahrens et al. (23) have noted the importance of bulk vapor flow for water removal and heat transfer in paper drying. In impulse drying, however, the mechanical compression of the wet sheet creates a saturated pore network which prevents vapor escape. Displacement can then occur as the gas pushes liquid away.

Some experimental evidence for steam displacement exists. This includes flash x-ray visualization of multiphase flow during impulse drying (24) and *in situ* measurements of vapor pressure and temperature during simulated impulse drying (25). The internal temperature propagation measurements of Sprague are also useful in this regard (26). Fine thermocouples were sandwiched between thin, wet sheets of bleached kraft paper. During impulse drying, the temperature at each layer was tracked in time. Sample results are given in Figure 2. Figure 2a shows the temperature at the felt-paper interface beneath a single sheet. Three thermocouples at different locations on that interface were used, two of which gave similar results. Nonuniformities may account for the third curve. The upper two curves show traits found in several of the measurements: a steep rise to a plateau above the ambient boiling temperature, followed by a rapid temperature rise which then levels off. Measurements at three transverse locations are shown in Figure 2b. Here, three sheets have been stacked, and single thermocouples have been placed between the sheets. The upper curve from the thermocouple closest to the surface does not show an intermediate plateau. The second curve, showing data from the interface between the middle and bottom sheets, does show an S-shaped rise followed by a nearly flat region.

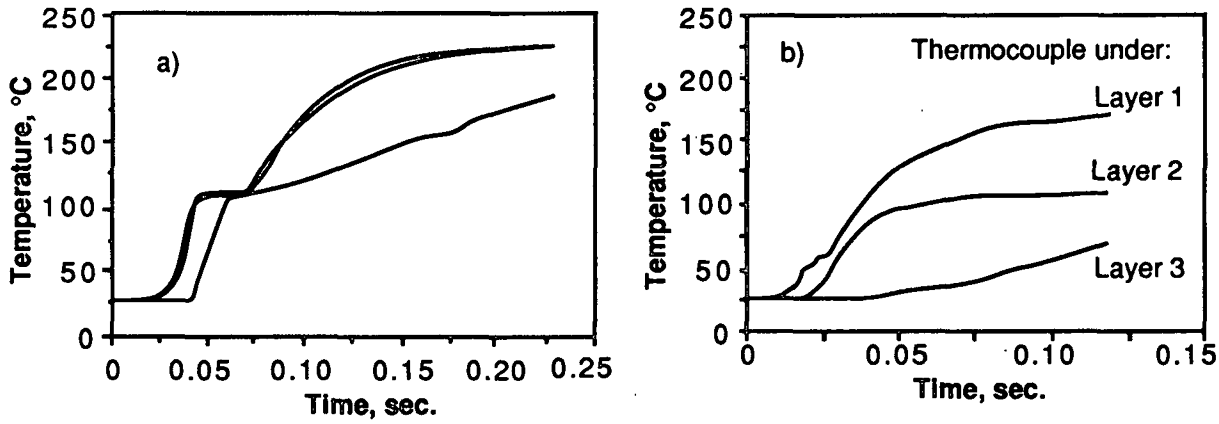

FIGURE 2. Temperature propagation in 50 g/m² sheets on a felt during impulse drying with a platen temperature of 260°C. a) Three simultaneous measurements at different positions under one sheet on a felt. b) Temperatures between three layers of sheets.

A vapor-liquid displacement mechanism can account for the above results. The existence of plateau regions above 100°C is evidence for a two-phase zone where the vapor and liquid are in equilibrium at an elevated pressure. The two-phase zone at any point may only be temporary, and as it moves away, a dry zone with higher temperatures follows. In some cases, the two-phase zone is very thin, so a sharp steam-water interface may exist. Regions of slow temperature rise show the effect of transient conduction heating through a saturated liquid zone. In short, the data are consistent with the proposed displacement mechanism of impulse drying, and provide evidence that extended two-phase zones may be formed during impulse drying. (This analysis was aided by an examination of the numerical results from this study.)

Displacement as a dewatering mechanism has been directly explored by Lindsay (27,28), who simultaneously applied gas pressure and mechanical compression to wet sheets. While the data were not intended to apply to impulse drying, the results confirm that sustained gas pressure in a compressed sheet can enhance water removal.

A pressurized vapor zone may also contribute to enhanced liquid water removal by preventing rewet (18). Rewet refers to the transfer of liquid water back to the sheet from a felt as the sheet and felt expand upon leaving a nip. The physics of rewet are still being debated, but all proposed mechanisms would be resisted by the presence of a pressurized gas phase in the sheet.

NUMERICAL MODELS

In order to explore the importance of various mechanisms in high-intensity processes such as impulse drying, numerical modeling is a useful tool. Recently, two different models have been applied to impulse drying to examine heat transfer and vapor formation effects. We will see that both models lead to similar conclusions about the role of vapor formation.

Several previous studies must be mentioned first. Analytical treatments of displacement processes relevant to impulse drying have been conducted by Ahrens (29) and Pounder (30). Pounder and Ahrens then extended these concepts to a numerical model that predicted both the pressing aspects and displacement features of impulse drying (31,32). The resulting model gave insight into the complexity of the impulse drying process and represented an ambitious first step in impulse drying modeling. While some aspects of the model were successful, the treatment of the different zones seems to have resulted in a number of unrealistic predictions showing periods of linear change punctuated with discontinuities (occasionally large spikes) during the transition from one regime to another (32). Predicted heat transfer rates, in particular, did not compare well with observation. The model may have been too ambitious, for accurate models of pressing alone, without heat transfer, still present challenges that have not been overcome.

Insight into the role of vapor in drying may be obtained from Holm's results with a numerical model of conventional multicylinder linerboard drying (22,33). His results showed that temperatures above 100°C in the web could occur, even under conventional drying conditions, resulting in significant bulk vapor flow and higher drying rates than in diffusion-controlled drying.

Recent IPST Results

Recently, Lindsay (18) developed a finite-difference moving-boundary model to examine heat transfer, vapor formation, and fluid flow in an idealized impulse drying process. The transient behavior of dry, two-phase and saturated zones in a one-dimensional, rigid porous medium was examined with a finite-difference moving-boundary model, MIPPS (Moving Interface Problems in Porous Systems). The problem included two internal moving boundaries each with changing temperature, pressure, and fluid velocity. Flow and heat transfer in the porous medium, including some capillary pressure effects, were accounted for. Temperature-dependent properties were used.

A two-phase equilibrium zone was allowed to form (34). Specifically, bound or trapped water in pores remained immobile as vapor advanced until the liquid had been evaporated by heat transfer. Sample results are shown in Figure 3. Predicted temperature profile results and the associated heat transfer mechanisms are qualitatively depicted in Figure 4. In these and other results presented below, sufficiently fine grids have been used to ensure results are grid-independent. Numerical errors are on the order of 2% and are insignificant compared to uncertainties in the physical properties of paper and to other limitations of the model.

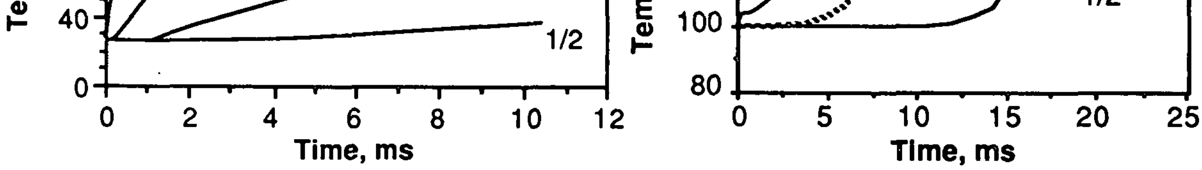

FIGURE 3. Two sample MIPPS-II predictions of local temperature histories in different paper sheets using different but realistic impulse drying conditions.

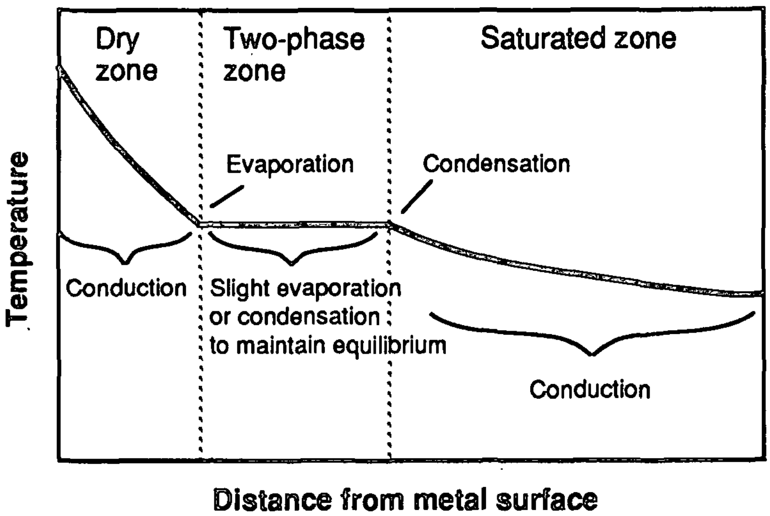

FIGURE 4. Temperature profile in a sheet and associated heat transfer processes during impulse drying (based on numerical predictions). Sketch is not drawn to scale.

In the sheet, heat transfer proceeds by conduction in the dry zone. Conduction into the two-phase region is largely balanced by vaporization of fluid at the boundary between the dry and two-phase regions. Likewise, conduction into the saturated liquid zone is largely supplied by condensation occurring at the boundary between the two-phase and saturated zones. Bulk steam pressure continually changes due to phase change or boundary motion, but is kept in equilibrium with the liquid water in the two-phase zone by allowing condensation or vaporization to occur throughout the cells in the two-phase zone as needed. Rigorous balance and equilibrium equations are used.

Predicted local rates of evaporation and condensation have nearly equal magnitudes, giving a net evaporation rate in the nip close to zero. The process of internal vaporization and condensation is analogous to a heat pipe and gives heat fluxes beyond that of conduction alone. Simultaneous evaporation and condensation in the sheet is not an assumption but is a direct consequence of thermodynamics and conservation of energy. Similar observations have also been made for conventional paper drying (35).

MIPPS has also been used to explore the importance of sheet permeability on impulse drying vapor formation. Numerical results show that an order-of-magnitude decrease in sheet permeability increases peak internal vapor pressures by a factor of 2 to 4. Sample results are shown in Figure 5 below, where vapor pressure predictions are made for two similar cases differing only in sheet permeability. The sensitivity of vapor pressure to sheet permeability is largely due to the effect of permeability on the displacement velocity of the liquid in the saturated zone. The faster the saturated zone moves toward the felt, the more volume there is for vapor expansion. Furthermore, as the liquid moves away from the hot surface, the temperature gradient driving heat transfer is reduced, so heat flux into the sheet drops more rapidly with time, and lower equilibrium vapor pressures are sustained. In terms of practical operation, a high permeability sheet will also allow the pressurized vapor to escape from the sheet more easily upon nip expansion. Orloff and Lindsay (11) recently provided experimental confirmation of the effect of sheet permeability on impulse drying behavior.

Currently, MIPPS is being used to examine the role of multilayer ceramic coatings in improving impulse drying performance. Simple heat transfer analysis fails to predict the large gains observed with the novel rolls; perhaps numerical results will offer some insight.

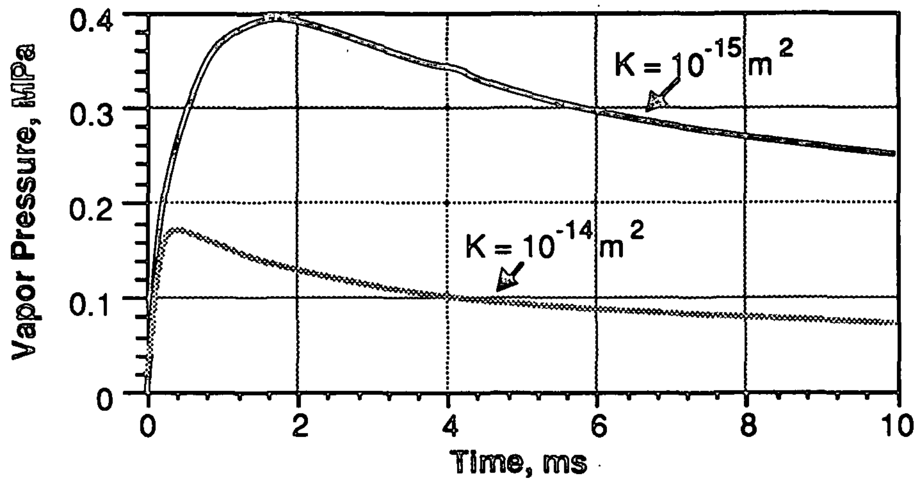

Figure 5. Effect of permeability on transient vapor pressure development. A 0.5-mm sheet initially at 87°C is exposed to a platen at 327°C. Sheet porosity is 50%, and immobile saturation is 20%.

Ramaswamy's Model of High-Intensity Drying

An extensive generalized model for paper drying under conventional and high-intensity conditions was developed at SUNY-Syracuse (36). The model has taken into account the various heat and mass transfer processes that are likely to take place during drying under conventional and high-intensity conditions, including pressure-driven bulk flow of liquid and vapor. The model equations representing the transport processes were solved using the finite difference method.

The model predictions were compared with the experimental results from Ahrens and Åström (21) for a 205-g/m^2 linerboard at a hot-plate temperature of 232°C. The predictions under high-intensity conditions showed that the pressurized vapor zone can expel liquid water in the initial phase of the high-intensity drying.

The model predictions for vapor pressure development and heat flux agreed well with experimental results except that the predicted vapor pressure decayed much faster. The high-intensity drying was completed in 7.6 seconds with an overall average drying rate of 110 kg/m^2 hr. The temperature rose quickly above 100°C inside the mat. The swift rise in pressure in the initial phase and then a drop in the first second is shown in Figure 6. The maximum pressure inside the mat was close to the hot surface and was about 1 atm gauge pressure.

During the initial phase, there was a buildup of saturation in the interior of the web. As shown in Figure 7, there was pressure-driven bulk flow of liquid from the hot surface toward the open surface. The interesting feature of the mass flux at 0.2 seconds is the large liquid flux at the open surface. This indicated that during this initial phase, a large amount of the liquid was pushed out of the web by the pressurized vapor zone.

The temperature, saturation, and pressure distribution within the mat during the drying process showed the development of three distinct zones: 1) a dry zone characterized by higher temperatures, low moisture, and constant pressure; 2) a wet zone with nonuniform saturation, almost constant temperature, and varying pressure; and 3) an intermediate or transition zone between the wet and dry zones.

As the sheet was dried, the dry zone advanced into the web from the hot surface side, and the location of the intermediate zone also moved farther into the web. The mass flux data (liquid and vapor flux) at the intermediate zone showed an interesting feature. As shown in Figure 8, at 3.2 seconds during the drying process, the dry zone extends up to position 4, and the wet zone extends over slices 6 to 10. The liquid flux at the hot surface and the open face was almost zero. The main vapor transport at the open surface occurs by diffusion and bulk flow. At the intermedi-

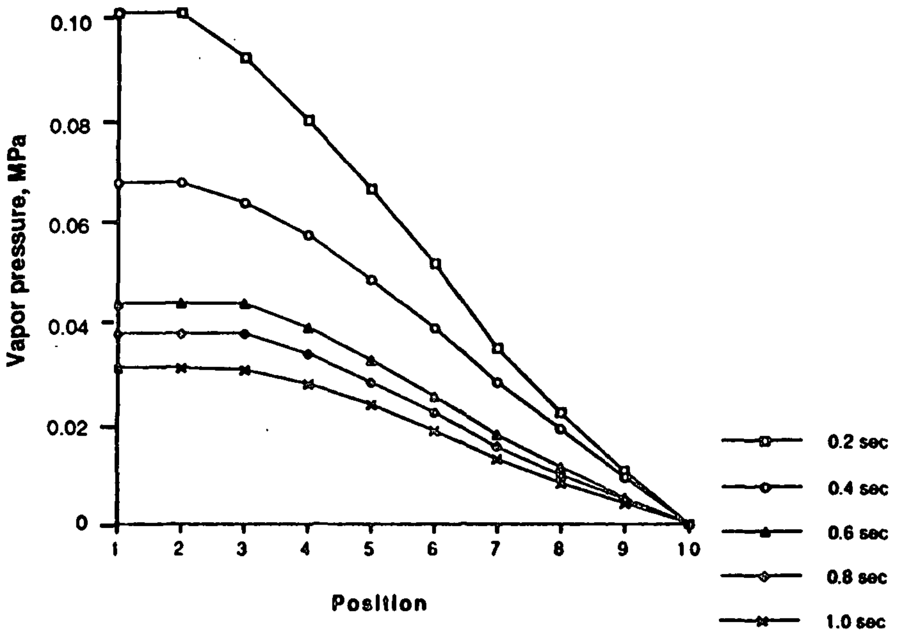

Figure 6. Pressure versus position in a sheet during high-intensity drying.

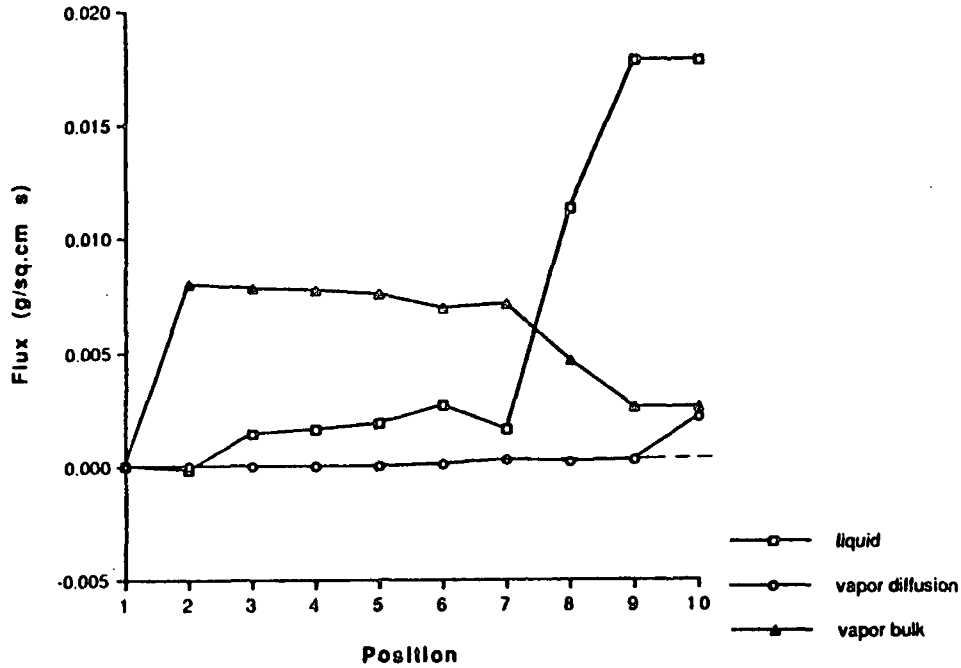

Figure 7. Mass flux versus position at 0.2 seconds during high-intensity drying.

ate zone (position 5), the liquid flux is negative, while the vapor flux is positive. This means that liquid in the intermediate zone is flowing toward the hot surface against the bulk vapor flow, similar to the flow in a classical heat pipe. As drying continued, the intermediate zone and its heat pipe advanced into the web. This "advancing heat pipe" was also observed in drying under conventional temperature conditions. The mass flux data also showed that the liquid flux in the dry zone was almost zero throughout the drying process.

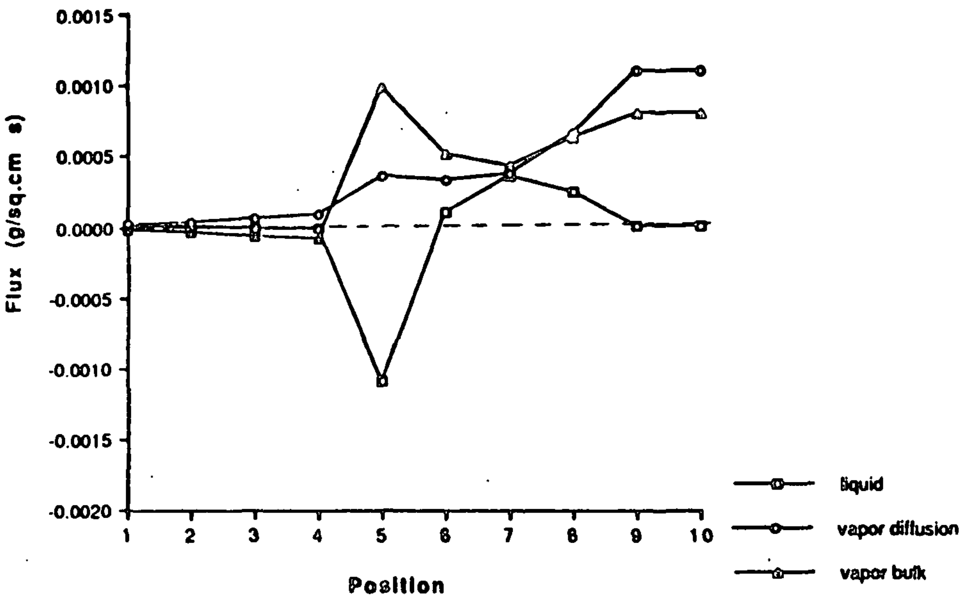

Figure 8. Mass flux versus position at 3.2 seconds during high-intensity drying.

The model predictions on heat flux also showed an advancing heat pipe mechanism. The energy for vaporization of liquid was supplied by conduction through the dry zone. Convection played an insignificant role in heat transfer even under high-intensity conditions.

The mass flux data also indicate that water removal due to liquid displacement was about 24% of the total water removed during high-intensity drying for the conditions studied. Most of the displacement occurred in the first second of drying. This finding is in agreement with Devlin's experimental results (37) for high-intensity drying (actually an early impulse drying study) at similar conditions. The drying rate in the initial phase of the high-intensity process was about 300 kg/m^2 hr and was mainly due to the bulk movement of liquid.

The model predictions reported here confirm Lindsay's findings on the development of high vapor pressures and a pressurized zone inside the mat during high-intensity drying. The vapor zone plays a significant role in pushing the liquid water out of the web during the initial phase and thereby giving rise to water removal rates that are significantly higher than what can be achieved by conventional drying or pressing operations. The model predictions show that the heat and mass transfer processes that take place inside a fiber mat during high-intensity drying can be characterized by an advancing heat pipe that moves away from the hot surface as the web is dried.

CONCLUSION

Two independent models of high-intensity processes, one directed toward impulse drying and one for general paper drying, both point to the importance of vapor formation in assisting water removal. Displacement of liquid water by a pressurized vapor zone is of particular importance in impulse drying and can occur in other drying processes as well, depending on the amount and distribution of liquid in the sheet. Both models show that cyclic vaporization and condensation in the sheet are an essential feature of the heat transfer mechanism; Ramaswamy's model, in particular, highlights the importance of an advancing heat-pipe mechanism. The numerical findings are consistent with a variety of experimental observations and are of value in interpreting some experimental results, such as temperature propagation curves in impulse drying.

Given that multiphase flow in paper has economic importance in drying processes, an improved understanding of multiphase flow in paper should be sought to further advance our understanding of these processes. Work is currently underway at IPST to accurately document relative permeabilities and other multiphase-flow parameters for fibrous media.

Work is underway to commercialize impulse drying using the ceramic roll concept. Other high-intensity paper drying processes are expected to be more widely used in the future.

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